Characterisation of electron beams generated by a plasma-cathode gun

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The paper is devoted to electron beam guns based on the emission of electrons from plasma of a hollow-cathode reflective discharge. The measuring of the diameter and brightness of beam with the rotating wire sensor and scanning slit device were performed. A gun capable of producing strongly focused electron beams of power up to 6 kW and energy up to 60 keV. The test piece welding was confirmed a good beam quality. A key finding from these studies was that the brightness of the electron beam generated by the gun with a plasma cathode is not inferior brightness beams obtained by thermionic cathodes. For example, the brightness of the beam with power up to 4 kW and energy of 60 keV was approximately $10^{10}$ A·m$^{-2}$·sr$^{-1}$ at the focal distance of 0.5 m. Beam diameter does not exceed 460 µm.

Introduction

Electron-beam guns with a plasma cathode based on the emission of electrons from a low-voltage discharge with a hollow cathode [1] have long been used in the beam technologies [2, 3]. In contrast to the widespread triode guns, guns with a plasma cathode are designed by a diode scheme. Current control in such guns is performed without grid electrode. The advantage of such a beam current control [4] is, in contrast to hot cathode triode gun, the electron-optical properties of the focused beam remain practically unchanged at the beam current variation. Within the broad range of the electron-beam experts is widely believed that the guns of this type provide a low beam current density because of the high electrons temperature by the emitting plasma. According to our estimates, based on the known formula of Langmuir [5], for typical parameters of the plasma cathode, the minimum size of a focused electron beam must not exceed a few tens of microns [6].

However, in experiments such a small diameter has not been reached for a long time for beam emitters using discharge processes. The reason was the underestimation of the influence of the magnetic field of the discharge chamber on the properties of the electron beam in the accelerating gap and the drift space of the gun. After the optimization of the magnetic field, electron beams with a power density of up to $10^7$ W/cm$^2$ at 60 keV electron energy can be generated. In addition to the power density in the focal spot, the brightness of the electron beam is equally important to evaluate the electron-optical parameters of the gun. High brightness makes it possible to use plasma-cathode EB guns for high-quality welding, applications involving pressure stage systems (non-vacuum, low-vacuum) or processes with high demands on beam quality such as EB drilling or rapid manufacturing or rapid prototyping. The results of our assessment of the beam generated by an electron gun with a plasma cathode are set out below.
**Test setup and measurement techniques**

The measurement of the beam radius $r_f$ at the focal spot and the convergence angle of the focused electron beam on guns with a plasma cathode was carried out at the installation shown in Fig.1. The main parts of the installation are the electron-beam gun developed by Elion Ltd. (Russia) for Perndorfer Maschinenbau KG (Austria), the vacuum chamber and probing system (Fig.1a).

Electrons emitted from plasma caused by an electric field are required for the operation of a plasma cathode gun. The emitting plasma is produced by a low-voltage reflective discharge with a hollow cathode [1].

The basic component of a gun is the discharge chamber, a ceramic-metal unit. Its primary function is to produce charged particles in a Penning-type gas discharge. A schematic diagram of the electrode assembly of a plasma-cathode electron gun is given in Fig.1b.

The discharge chamber is formed by a hollow cathode (1), a cylindrical anode (2), and an emitter cathode (4). The voltage (DP) is necessary for the discharge initiation and operation. It is applied between the cathodes and the anode. A permanent magnet (3) creates a magnetic field of $(0.8\pm1)\cdot10^{-1}\text{T}$ in the space between the hollow cathode and the emitter cathode. The working gas (usually air) is fed into the discharge chamber through the hollow cathode channel and is pumped out through the channel in the emitter cathode. The accelerating voltage (HVP) up to 60 kV is applied to the emitter cathode (4) relative to the grounded accelerating electrode (5). The plasma electrons that leave the chamber through the emitter cathode channel are accelerated in the high-voltage electric field and form a beam, which is focused by the magnetic field of the focusing lens (7). The deflection coils (8) are used for beam deflection. It is common to use a low-voltage form of glow discharge, i.e. with a voltage of $350\div450\text{V}$. The pressure in the discharge chamber is $(0.5\div1)\cdot10^{-1}\text{mbar}$. The value of the gas flow is small and usually does not exceed $(4.2\div5.6)\cdot10^{-3}\text{mbar}l/s$. The maximum beam current is $150\text{mA}$.

**Measurement of electron beam diameter**

One of the most important parameters of an electron beam is its diameter. There are two groups of methods of measurement: the thin wire sensor is moving at high speed across the beam (rotating wire) or a beam intersects a stationary sensor with the deflection system (scanning slit). The current density of an electron beam is usually distributed in the form of a Gaussian curve. Depending on the application, a
diameter is defined as the width of an area covered with a fixed fraction of the maximum value or the integral of the distribution. The half value width (FWHM, Full Width at Half Maximum), well-established in industry and science for the characterization of electron beams, is used in this work. This is the width of the range in which the power density exceeds at least half the maximum value. In this paper, measuring the diameter of the electron beam was carried out both by the slit and by the rotating wire sensor.

For the first method (scanning slit), a system designed by TWI Ltd. was used (Fig. 2).

The TWI EB probe system comprises the following:
- The two finger probe with integrated Faraday cup;
- A beam sink, or dump, capable of withstanding the maximum beam power for extended periods;
- A data acquisition system based around an industrial PC.

The probe heads measure a sample of the beam current as it passes through a narrow slit, as the beam is swept across the probe in a direction orthogonal to the alignment of the slit (Fig. 3). The main information gathered by the probe is the width of the beam in the direction of the sweep (Fig. 3). Typically, this width is defined to be the full width of the beam at half of the maximum measured current (FWHM). A second probe is orientated perpendicular to the first and is used to measure the width in the orthogonal direction. In addition to the width of the beam, the beam speed can be measured by collecting current from the probe body. This allows an accurate measure of the velocity of the beam sweep, and enables the width measurements to be converted from a duration to a distance. The two-finger probe relies on the beam moving over the slit at a constant speed to acquire good quality data. The speed should be consistent across both the X and Y finger to ensure that the probe data is comparable. A Faraday cup is designed as an optional feature, to allow the total beam current to be measured. The sensor is a cup with an aperture size sufficient to capture the entire beam as it is swept over – thus enabling the total beam current to be measured.

The beam path was chosen as a triangular pattern moving out over the X finger (1), tracking across the Faraday cup (2) and falling back to the free fall position across the Y finger (3) as shown by the line in Fig. 2.

Fig. 4 shows a view of the signal curve on the oscilloscope screen.

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Elion Ltd. designed a measurement system with a rotating wire sensor (Fig.5) in collaboration with IW.

![Fig.5. General view of the Elion EB probe device.](image)

A unique feature of the designed system is the use of two parallel wires with 0.11 mm diameter. The measurement signals are recorded by digital storage oscilloscope (DSO). Both single wires produce distinct pulses. The length of the time interval between these pulses and the fixed spatial distance of 30mm give a value for the travel speed at the radial position. This value can be used to convert the time-resolved signals of each individual wire to a spatially resolved power density distribution.

### Measurement of electron beam diameter

For a beam with Gaussian power distribution brightness can be written as

\[
B = \frac{J_{\text{max}}}{\Omega},
\]

where

\[
J_{\text{max}} = \frac{i_{\text{beam}}}{\pi \cdot r_i^2}.
\]

\(J_{\text{max}}\) is the maximum current density in the focal plane, \(i_{\text{beam}}\) is the beam current, \(r_f\) is the beam radius at the focal plane.

The solid angle of the beam envelope is

\[
\Omega = 2\pi (1 - \cos \theta) = 4\pi \sin^2 (\theta/2),
\]

where \(\theta\) is the half angle of the beam divergence.

For small angles, we can approximate that

\[
\Omega = \pi \theta^2.
\]

Therefore, we can write

\[
B = \frac{i_{\text{beam}}}{(\pi r_f^2 \theta)}. \tag{5}
\]

The brightness of the electron-beam gun with a plasma cathode can be calculated from equation (5) and using experimental values of the beam diameter at several positions.

![Fig.6. Illustration of the method for calculating convergence angle.](image)
In practice, the convergence angle of the electron beam was measured according to Fig. 6.

At a given working distance and beam current the electron beam is sharply focused and the beam diameter is measured giving the so-called sharp-focus radius $r_f$ for this plane. After that, while keeping the focusing current unchanged, the beam radius is measured along the beam axis by positioning the probing device at several planes.

Thus, a beam profile along the $z$-axis is obtained and it can be approximated by a linear dependence

$$r_{beam}(z) = az + r_f.$$

The beam radius in the focusing lens $r_i$ can be calculated by

$$tg(\theta) = \frac{r_i - r_f}{b},$$

where $b$ is the distance of the sharp focus plane to the focusing lens and $\theta$ is the convergence angle of the electron beam.

**Conclusion**

The brightness of the electron beam generated by the gun with a plasma cathode, made at the beam current range of 10–60 mA was measured. The measurement was carried out at the accelerating voltage 60 kV, the plasma gas flow rate $4.2 \cdot 10^{-3}$ mbar·l/s and the focal plane of the electron beam was set to 520 mm. Table 1 shows the results of our measurement giving the diameter of the focused electron beam, as well as the calculated brightness, the beam diameter in the lens and the convergence angle, respectively.

As evident from Table 1, the brightness of an electron beam from the plasma cathode gun is not inferior compared to beams from thermionic cathodes of LaB$_6$ and of superior brightness compared to tungsten filament cathodes.

The test pieces were made for qualitative evaluation of the measured parameters of the electron beam. Macrosection of the sample is shown in Fig. 7.

![Fig.7. Crosssection of the welds.](image)

A narrow and deep penetration profile with parallel walls characterizes the beam with a small convergence angle, which correlates with the results of measurements the beam parameters.

This work was carrying out as a part of the FastEBM project in Seventh Framework Programme for Research (EU). The FastEBM project will develop a higher power electron-beam system for Additive Layered Manufacturing [8] without compromising the resolution through keeping the beam diameter small. This project requires a beam of a diameter 200 µm at a working distance of 520 mm from the lens center plane. As aberration of the beam is in part dependent upon its diameter in the deflection coils, which are sited just after the lens, this limits the maximum beam diameter in the lens. In practical terms, the beam diameter maximum in the lens center plane has been constrained to 10 mm. This allows the beam angle and consequently the required brightness to be derived at the focal distance of 520 mm (at 60 kV, 60 mA the

<table>
<thead>
<tr>
<th>Beam current (mA)</th>
<th>Focus current (mA)</th>
<th>Beam diameter in lens (mm)</th>
<th>Beam diameter at focus (µm)</th>
<th>Convergence angle (rad)</th>
<th>Brightness (A·m$^{-2}$·sr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>675</td>
<td>2.18</td>
<td>550</td>
<td>1.6·10$^{-3}$</td>
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</tr>
<tr>
<td>20</td>
<td>675</td>
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<td>560</td>
<td>1.5·10$^{-3}$</td>
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<tr>
<td>40</td>
<td>675</td>
<td>3.18</td>
<td>580</td>
<td>2.5·10$^{-3}$</td>
<td>0.8·10$^{10}$</td>
</tr>
<tr>
<td>60</td>
<td>675</td>
<td>3.06</td>
<td>460</td>
<td>2.7·10$^{-3}$</td>
<td>1.6·10$^{10}$</td>
</tr>
</tbody>
</table>

Tungsten hairpin filament cathode$^2$ 5·10$^8$

Tungsten hairpin tip cathode$^2$ 5·10$^{10}$

LaB$_6$ cathode$^2$ 5·10$^{10}$

LaB$_6$ sharp tip cathode$^7$ 5·10$^{11}$

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**Table 1**

The results of measuring the electron beam brightness.
required brightness is $6.6 \times 10^9 \text{A} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$). The probing results have shown that the measured beam brightness at 60 kV is higher than the currently used thermal emitter triode gun and that the plasma cathode gun brightness ($1.6 \times 10^{10} \text{A} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$) is greater than the project required beam brightness. The probing results also show that to meet the requirements alternative electron optics are required such that the beam diameter in the objective lens is expanded to some 10 mm to allow projection 520 mm and production of a 200 µm spot diameter.

The project aims to increase the power of the gun system to 10 kW. The probing measurements indicate that brightness is increasing with beam power and if this trend continues a brightness of $4 \times 10^{10} \text{A} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$ would be expected at 10 kW. The required brightness is $1.8 \times 10^{10} \text{A} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$ to achieve a focused beam diameter of 200 µm. Consequently, this looks promising, although measurements of higher power beams would be required to verify the performance of the gun at levels from 3.6 kW to 10 kW.

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